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RATE OF MASS TRANSFER IN A SEMIFLUIDIZED BED

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Abstract – Data on mass transfer in a semifluidized bed have been obtained for 2-naphthol-, succinic acid-, and ammonium oxalate–water systems. The parameters investigated include particle size (0.043–0.187 cm), initial bed height (2–10 cm), bed expansion ratio (3–10) and flow rates. Two correlations have been suggested for predicting volumetric mass-transfer coefficients, $k_L a$. In the first case, $k_L a$ has been correlated as a function of particle Reynolds number, bed expansion ratio and particle-to-column diameter ratio, while in the latter, the generalized approach for predicting mass-transfer coefficient applicable to packed and fluidized beds, has been extended to semifluidization.

NOMENCLATURE

a,	surface area of solid per unit volume of the bed [m^2/m^3];
C,	concentration of solid in liquid [kg/kg];
D,	diffusion coefficient [m^2/s];
d_p,	particle diameter [m];
D_T,	column diameter [m];
G,	mass velocity based on empty tube [kg/s · m^2];
h,	height of the semifluidizer (or height) [m];
$k_l a$,	local volumetric mass-transfer coefficient [kg/s · m^3 · ΔC];
$k_L a$,	overall volumetric mass transfer coefficient in a semifluidized bed [kg/s · m^3 · ΔC];
R,	bed expansion ratio, h/h_0;
Re_p,	particle Reynolds number, $d_p G/\mu$;
Sc,	Schmidt number, $\mu/\rho D$;
u,	superficial fluid velocity [m/s].

Greek symbols

ε,	voidage;
ΔC,	log mean concentration difference, equation (8);
ρ,	fluid density [kg/m^3];
μ,	fluid viscosity [N · s/m^2].

Subscripts

f,	fluidized section of the semifluidized bed;
i,	interface;
0,	initial;
p,	packed section of the semifluidized bed;
s,	saturation;
sf,	semifluidization;
1,	inlet;
2,	outlet.

INTRODUCTION

SEMIFLUIDIZATION is a two-phase phenomenon which can be viewed as the combination of a batch fluidized bed at the bottom and a fixed bed at the top. Such a bed can be formed by providing sufficient space for the free expansion of a fluidized bed and then arresting the escape of particles by means of a top restraint. This method of fluid–solid contact can be regarded as a compromise between the fixed and fluidized beds wherein the disadvantages of fluidized bed, namely back-mixing of solids, attrition of particles and erosion of surface and those of packed bed like non-uniformity of temperature, segregation of solids and channeling are taken care of, at least, partially. A semifluidized bed has been shown [1, 2] to be ideal for exothermic catalytic reactions like vapour phase oxidation and chlorination of hydrocarbons. An optimum performance may be obtained with combined reactors of the mixed tubular model. A potential application of this technique is visualized in the field of hydrometallurgical extraction of metals or in the case of ion-exchange columns.

Fan *et al.* [3, 4] and Govindrajan and Sen Gupta [5] reported some data on mass transfer in semifluidized bed for benzoic acid–water system. The mass-transfer coefficient, k_L has been estimated by Fan and co-workers on the basis of surface area of particles as determined from permeability experiments. This method, for obvious reasons, gives lower values of surface area. Again, the extent of packed bed formed [6] will depend on the rate of flow of the fluid, the particle characteristics and the bed expansion ratio, and as such, the surface area available for the mass transfer will be greatly influenced by these parameters. Consequently, an exact evaluation of k_L becomes difficult, if not impossible. To obviate this difficulty, Govindrajan and Sen Gupta suggested the use of volumetric mass-transfer coefficient, $k_L a$ for the entire semifluidized bed, but the correlation proposed is restricted to benzoic acid–water system only.

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Table 1. Ranges of parameters investigated

Sl. No.	Material	Density (kg/m^3)	Size, d_p, (m × 10^3)	Saturation concentration (at 30°C) C_s (kg/kg water × 10^3)	Diffusivity, D (m^2/s × 10^{10})	Initial bed height, h_0 (m × 10^2)	Bed expansion ratio, R	Reynolds number, Re_p	k_La (kg/s · m^3 × ΔC)
1.	2-Naphthol	1217	0.697, 0.949 1.340, 1.867	0.68	7.10	0.50–10	3.5–10.0	10.00–110.50	61–276
2.	Succinic acid	1572	0.697, 0.949	74.00	8.71	2–4	2.623–6.680	17.63–39.84	127.298
3.	Ammonium oxalate	1501	1.088	70.00	7.49	2–4	2–4	25.8–293.3	62–108
4.	(a) Benzoic acid*	1199	0.697, 0.949	4.17	7.84	4.49–8.50	1.63–4.29	24.3–56.4	85–208
	(b) Benzoic acid†	1199	0.795, 1.356 1.375, 2.103	4.17	7.84	9.16–17.95	1.37–2.11	5.12–122.63	75–169

*Data reported by Fan *et al.* [3, 4].
†Data reported by Govindrajan and Sen Gupta [5].

EXPERIMENTAL

The semifluidizer comprises a glass column of dimensions shown in Fig. 1. The top and bottom grids are made of 150 mesh stainless steel screen. For withdrawing the effluent an outlet has been provided at the top. A calming section is connected to the bottom of the column by means of a B-50 joint. The other accessories include a centrifugal pump and devices for measuring the pressure drop and flow rate of the liquid.

For a desired bed expansion ratio, a known amount of material of a definite feed size is charged into the column and water is allowed to flow at an increasing rate. Between minimum and maximum semifluidization velocities, the effluents are collected corresponding to different flow rates and analyzed. The samples of 2-naphthol and succinic acid are titrated with standard alkali (NaOH) using the method of conductometric titration and that of ammonium oxalate against $KMnO_4$ solution.

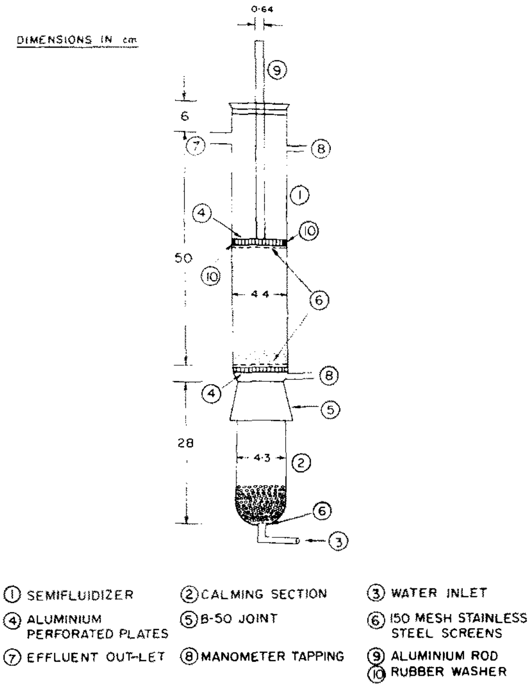

FIG. 1. Semifluidizer for mass-transfer studies.

The ranges of parameters investigated are shown in Table 1.

OVERALL MASS-TRANSFER COEFFICIENT

Based on certain simplifying assumptions Fan *et al.* [4] obtained the following rate equation for mass transfer between solid and liquid, which is valid for any bed height,

$$G[\mathrm{d}C/\mathrm{d}h] = k_l a(C_s - C) \tag{1}$$

or,

$$G\int \frac{\mathrm{d}C}{C_s - C} = \int k_l a\,\mathrm{d}h. \tag{2}$$

Integration of equation (2) runs into difficulty because of the discontinuity in the concentration gradient at the interface of the packed and fluidized sections.

Assuming that C_i is the interface concentration, equation (2) can be integrated over the limits of packed and fluidized sections as follows:

$$G\int_{C_1}^{C_i} \frac{\mathrm{d}C}{C_s - C} + G\int_{C_i}^{C_2} \frac{\mathrm{d}C}{C_s - C} = \int_0^{h_f} (k_1 a)_f\,\mathrm{d}h + \int_{h_f}^{h} (k_1 a)_p\,\mathrm{d}h \tag{3}$$

or,

$$G \ln \frac{C_s - C_1}{C_s - C_2} = \int_0^{h_f} (k_1 a)_f\,\mathrm{d}h + \int_{h_f}^{h} (k_1 a)_p\,\mathrm{d}h. \tag{4}$$

If the overall value of mass-transfer coefficient k_La for the semifluidized bed is defined as,

$$(k_La) = \left[\int_0^{h_f} (k_1 a)_f\,\mathrm{d}h + \int_{h_f}^{h} (k_1 a)_p\,\mathrm{d}h\right]\Big/ h \tag{5}$$

then, the following expression can be obtained for k_La,

$$(k_La) = \frac{G}{h} \ln \frac{C_s - C_1}{C_s - C_2}. \qquad (6)$$

In terms of log mean concentration difference, equation (6) can be written as,

$$(k_La) = \frac{G}{h} \frac{C_2 - C_1}{\Delta C} \qquad (7)$$

where,

$$\Delta C = \frac{C_2 - C_1}{\ln[(C_s - C_1)/(C_s - C_2)]}. \qquad (8)$$

By knowing the inlet, outlet and saturation concentrations and by fixing the height of the semifluidizer, it is possible to determine the values of k_La corresponding to any flow rate within the limits of semifluidization.

RESULTS AND DISCUSSION

The experimental values of k_La have been found [6] to increase with an increase in the fluid velocity and a decrease in the bed expansion ratio, the initial bed height and the particle size. These findings are quite consistent with the observations made earlier by Leva [7] for packed and fluidized beds and Fan *et al.* [4] for the semifluidized bed. The dependence of k_La on the various operating conditions has been correlated empirically as follows:

$$k_La = 1.06 \times 10^{-3} Re_p^{0.72} R^{-0.79} \times (h_0/D_T)^{-0.72} (D_T/d_p)^{0.95}. \qquad (9)$$

Figure 2 shows a comparison between the predicted and experimental values of k_La and a fairly good agreement is observed. The large deviations in some cases may be attributed to the flocculation tendency of benzoic acid. Data reported by Fan *et al.* [4] and Govindrajan and Sen Gupta [5] are also comparable with those predicted using equation (9).

An alternative approach has been made for correlating the mass-transfer data by using the method suggested by Beek [8] for packed and fluidized beds. By processing all the present data for 2-naphthol, succinic acid and ammonium oxalate along with those reported by earlier workers [4, 5] for benzoic acid–water system, an empirical relationship has been developed. Thus,

$$(k_La/u)(\varepsilon_{sf})(Sc)^{2/3} = 27.64\, Re_p^{-0.5}. \qquad (10)$$

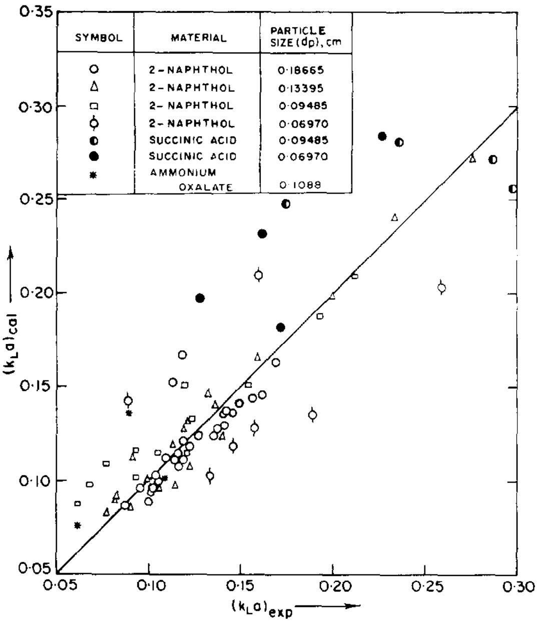

FIG. 2. Comparison of predicted and experimental values of volumetric mass-transfer coefficient (k_La).

It is observed that equation (10) can predict the mass-transfer coefficient quite accurately. Both equations (9) and (10) are of generalized nature having incorporated the effects of various system parameters on k_La. As against these, correlations reported earlier [4, 5] are limited to benzoic acid–water system only.

It may, however, be noted that be it heat or mass transfer, a semifluidized bed under identical conditions will have performance in between the fixed and fluidized beds. Considering its specific uses, the relatively low transfer coefficient should not be looked upon as a deterrent.

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FLUX DE TRANSFERT MASSIQUE DANS UN LIT SEMI-FLUIDISE

Résumé — On a obtenu des résultats de transfert massique dans un lit semi-fluidisé pour des systèmes eau et 2-naphtol, ou acide succinique ou oxalate d'ammonium. Les paramètres étudiés sont la taille des particules (0,043–0,187 cm), la hauteur initiale du lit (2–10 cm), le taux d'expansion du lit (3–10) et les vittesses de l'écoulement. On propose deux formules pour prédire les coefficients volumétriques de transfert massique k_La. Dans le premier cas k_La est exprimé en fonction du nombre de Reynolds de la particule, du taux d'expansion du lit et du rapport des diamètres de la particule et de la colonne, tandis que dans le second cas l'approche générale des lits fixes ou fluidisés est étendue à la semi-fluidisation.

STOFFÜBERGANG IN EINEM SEMIFLUIDATBETT

Zusammenfassung—Für Systeme von Naphthol, Bernsteinsäure und Ammoniumoxalat mit Wasser wurden Messungen zum Stoffübergang in einem Semifluidatbett gemacht. Die untersuchten Parameter sind: Größe der Partikel (0,043–0,187 cm), Anfangshöhe des Bettes (2–10 cm) Ausdehnungsverhältnis des Bettes (3–10) und Mengenströme. Zwei Gleichungen wurden für die Berechnung des volumetrischen Stoffübergangskoeffizienten k_La vorgeschlagen. Im ersten Fall wurde k_La als Funktion der Partikel-Reynolds-Zahl, des Bettausdehnungsverhältnisses und des Verhältnisses von Partikel- zu Säulendurchmesser dargestellt, während im zweiten Fall der allgemeine Ansatz zur Berechnung des Stoffübergangskoeffizienten für Festbett und Fließbett auf den semifluiden Zustand erweitert wurde.

ИНТЕНСИВНОСТЬ МАССОПЕРЕНОСА В ПОЛУПСЕВДООЖИЖЕННОМ СЛОЕ

Аннотация — Получены данные по массопереносу в полупсевдоожиженном слое для систем 2-нафтол-янтарная кислота и оксалат аммония–вода. Исследовалось влияние размера частиц (0,043–0,187 см), начальной высоты слоя (2–10 см), относительного расширения слоя (3–10) и скорости фильтрации дисперсионной среды. Предложены две обобщенные зависимости для расчёта коэффициентов массопереноса k_La по объёму слоя. В первом выражении найдена зависимость k_La от числа Рейнольдса для частиц, относительного расширения слоя и отношения диаметров частиц и колонны. Во второй зависимости обобщенный подход к расчёту коэффициента массопереноса для плотных и псевдоожиженных слоев распространен на случай полупсевдоожижения.